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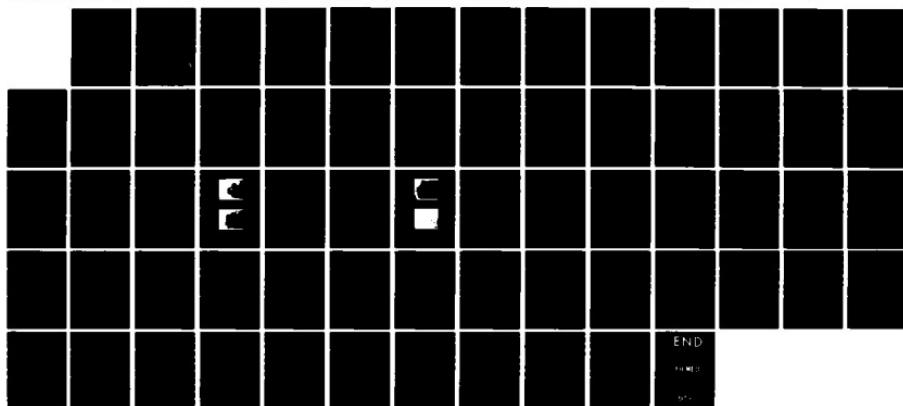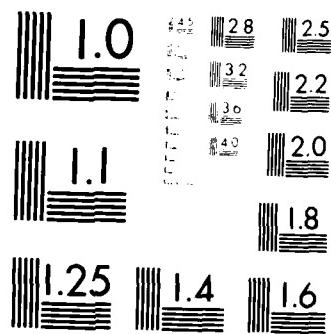
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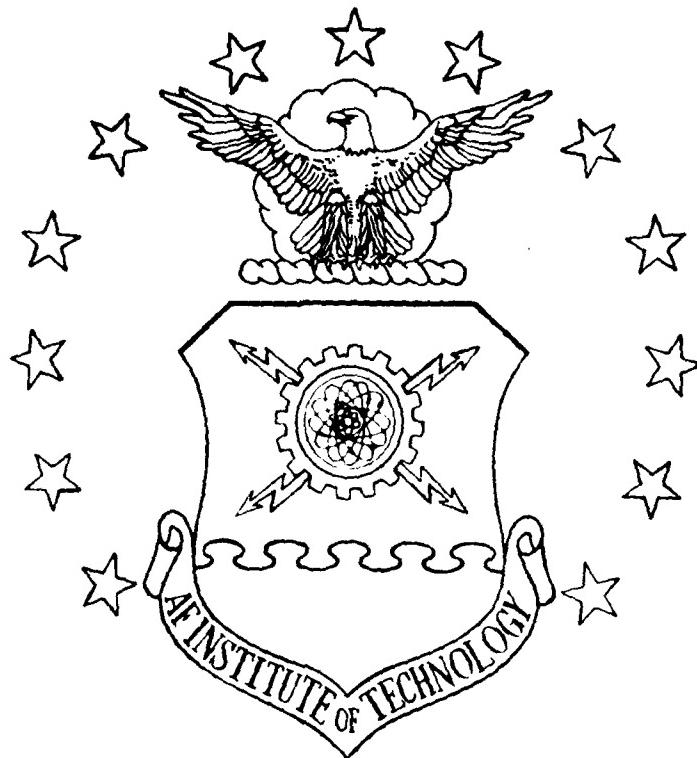
AN EXPERIMENTAL STUDY OF CLUSTERED,

TWO-DIMENSIONAL ROCKET NOZZLES

THESIS

David R. Bjurstrom
Captain, USAF

AFIT/GAE/AA/84D-1

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DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY

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Wright-Patterson Air Force Base, Ohio

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THESIS

Presented to the Faculty of the School of Engineering

of the Air Force Institute of Technology

Air University

In Partial Fulfillment of the

Requirements for the Degree of

Master of Science

David R. Bjurstrom, B.S.E.

Captain, USAF

December 1984

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Preface

The motivation behind deciding on an experimental thesis was the desire to build a mechanism and then see it put to good use. This project has provided for both of these desires. At certain times the frustration level was high, but the end result was certainly rewarding.

When this type of an endeavor is undertaken you quickly become aware of your own limitations. It is then that you can fully appreciate the guidance and assistance of the people associated with AFIT.

My thesis advisor, Dr. William Elrod, is a marvel. Not only was he always ready and willing to help, but he seemed to take the project beyond the technical content and was able to relate to me on a person to person level. He has my sincere respect and gratitude. The other members of my committee, Maj. E. Jumper and Capt. W. Cox, each made important contributions to the project. Their support and advice was also appreciated.

Two other groups must be mentioned. The lab technicians, Nick Yardich, Leroy Cannon, and Harley Linville, have helped daily throughout this enterprise. Also I would like to thank Carl Shortt and John Brohas of the fabrication shop. It has been a true pleasure to work with such craftsmen.

Finally, my thanks go out to my family. Without their support and love the help offered by all the others would have made little difference. It is through the difficult times that family ties are strengthened.

David R. Bjurstrom

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A_E nozzle exit area (in^2)

A_T nozzle throat area (in^2)

AR   nozzle area ratio

        $= A_E / A_T$

g_c conversion factor

        $= 32.17 \ (lbm\text{-}f)/(lbf\text{-}s^2)$

M_E exit Mach number

m mass flow rate (lbm/s)

P_A tank back pressure $(psia)$

P_C chamber pressure $(psia)$

P_E nozzle exit pressure $(psia)$

P_1 top exit plane pressure $(psia)$

P_2 center exit plane pressure $(psia)$

P_3 bottom exit plane pressure $(psia)$

PR   pressure ratio

        $= P_C / P_A$

T thrust

U_E nozzle exit velocity (f/s)

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ABSTRACT

This research involved the investigation of pressure and flow fields in the base region of clustered nozzles during cold flow testing. Nozzle exit conditions simulating altitudes up to 75,000 feet and chamber-to-back pressure ratios up to 200 were used. The nozzle clusters considered were made up of a pair of two-dimensional supersonic convergent-divergent nozzles with a design exit Mach number of 3.68. Three nozzle sets were studied; each having different spacing between the nozzles. A Schlieren system that allowed for both still photographs and film was used to investigate the flow fields.

The results of this study indicate that the pressure fields in the base region of a nozzle cluster are heavily dependent on both geometry and on the operating altitude. The outer wall of the test section adjacent to the nozzles was observed to significantly affect the flow patterns and measured pressures. Potential influences on performance exist due both to changes in the gas dynamics of the flow and the appearance of additional pressure-area forces.

AN EXPERIMENTAL STUDY OF CLUSTERED, TWO-DIMENSIONAL ROCKET NOZZLES

I   INTRODUCTION

The concept of grouping multiple rocket motors into a cluster arrangement has been examined for some twenty-five years. Early work by Goethert (1) in conjunction with the testing of the Polaris missile suggested the possibility of increased performance due to clustering. In a previous AFIT study, Lester (5) examined the potential performance effects of nozzle clusters due both to exhaust plumes interacting and plume interaction with a surrounding aerodynamic shroud.

This potential for increased performance will likely generate new designs incorporating clustered nozzles. Additional work is necessary to understand what is happening within the exhaust flow field of clustered nozzles in order to predict and exploit any possible performance augmentation. One example of a near future application is the work that is being done at the Air Force Rocket Propulsion Laboratory (AFRPL) in support of a Space Sortie Vehicle. This reusable system would be able to deliver small payloads to low orbit after being launched from a modified transport type aircraft. For aerodynamic reasons

and in an effort to speed development, use of a clustered arrangement of existing rocket engines is being considered. It is anticipated that performance may be affected both by the interaction of the exhausts with each other and with an aerodynamic shroud that is under consideration.

Theory

Following the suggestion of Lester (5), the effect of exhaust plume interaction in clustered nozzles can be explained as follows. Using conservation of momentum, a relation for nozzle thrust can be developed that states:

$$T = mU_E/g_c + (P_E - P_A)A_E \qquad (1)$$

where

T = thrust (lbf)
m = mass flow rate (lbm/s)
U_E = exit velocity (f/s)
P_E = exit pressure (psi)
P_A = ambient pressure (psi)
A_E = nozzle exit area (in)
g_c = conversion factor
    = 32.17 (lbm-f)/(lbf-s^2)

From this relation, it is evident that thrust can be expressed as the sum of two different phenomena. The first term is the product of the mass flow rate and the gas exhaust velocity with respect to the vehicle (6:25). This factor is the thrust due to the momentum flux and is usually the larger of the two. The second half of the expression is a pressure area term, often referred to as the pressure thrust. This additional force, usually small

compared to the momentum flux when the engine is operating near design altitude, will be present in a supersonic nozzle whenever the gas exit pressure is different from the ambient pressure. Further, the effect is sometimes sizable as demonstrated in the case of the Space Shuttle main engine which has a thrust of 375,000 lbf at sea level and a thrust of 470,000 lbf in vacuum. In this case the overexpansion at sea level actually causes a pressure drag or negative thrust; while in a vacuum a pressure thrust or positive contribution is encountered.

If the pressure at the nozzle exit is less than the local ambient pressure an oblique shock pattern is generated to adjust the two pressures and the exhaust jet contracts downstream (3:410-411; 6:56-61). This situation is referred to as overexpanded flow and contributes a negative pressure area term or a decrease in thrust as is the case of the Space Shuttle engine at sea level. The converse situation develops when the exit pressure exceeds ambient and is termed underexpanded flow. In this region, expansion and compression waves equalize the pressures and the jet will expand outward. In this situation, the pressure-area thrust contribution is positive as in the case of the Space Shuttle engine operating in a vacuum. The third case is the perfectly expanded nozzle where the two pressures are equal. This optimal situation will exist only at one altitude (i.e., the design altitude) as the vehicle ascends and results in no spreading or contracting of the plume.

Objectives

Previous thesis work done by Hibson (2) and Lester (5) studied the effects of clustering on the performance of rocket engine type nozzles. This project will continue that work with these specific objectives:

1. To design, build, and test an experimental apparatus to examine clustered nozzles under conditions found at high altitudes.

2. To experimentally analyze the pressures encountered in the nozzle base region due to:

   a. the interaction of two nozzle exhausts, and

   b. the interaction between an exhaust and a shroud.

The greatest limitation encountered in the prior research was the relatively small maximum pressure ratios that could be generated using sea level ambient conditions. The main difference in the present work will be the use of low back pressures to generate higher pressure ratios and simulate high altitude conditions.

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II EXPERIMENTAL APPARATUS

The central consideration behind the design of the apparatus was the need to generate much higher ratios of chamber pressure to back pressure than were obtained in the previous work by Hibson and Lester. To accomplish this, it was necessary to greatly lower the back pressure by the use of the vacuum system and a large tank into which the flow could be exhausted.

Flow System

Compressed air at 100 psi was supplied by a compressor and delivered via a three inch hose through a quick opening valve into a stilling chamber (see Fig. 1). The chamber assured that the air was flowing uniformly into the test section. After passing through the test section, the air exited into the large tank connected to the vacuum system. Ten inch square optical quality glass windows were mounted into the sides of the large tank to allow for Schlieren photographs of the flow as it exited the nozzles. To facilitate transducer calibration, a 0.25 inch outside diameter line was connected from the 100 psi air supply through a small valve into the stilling chamber. This additional air supply route allowed for incremental adjustment of the chamber pressure. To remove both particles and moisture from the air supply an internal
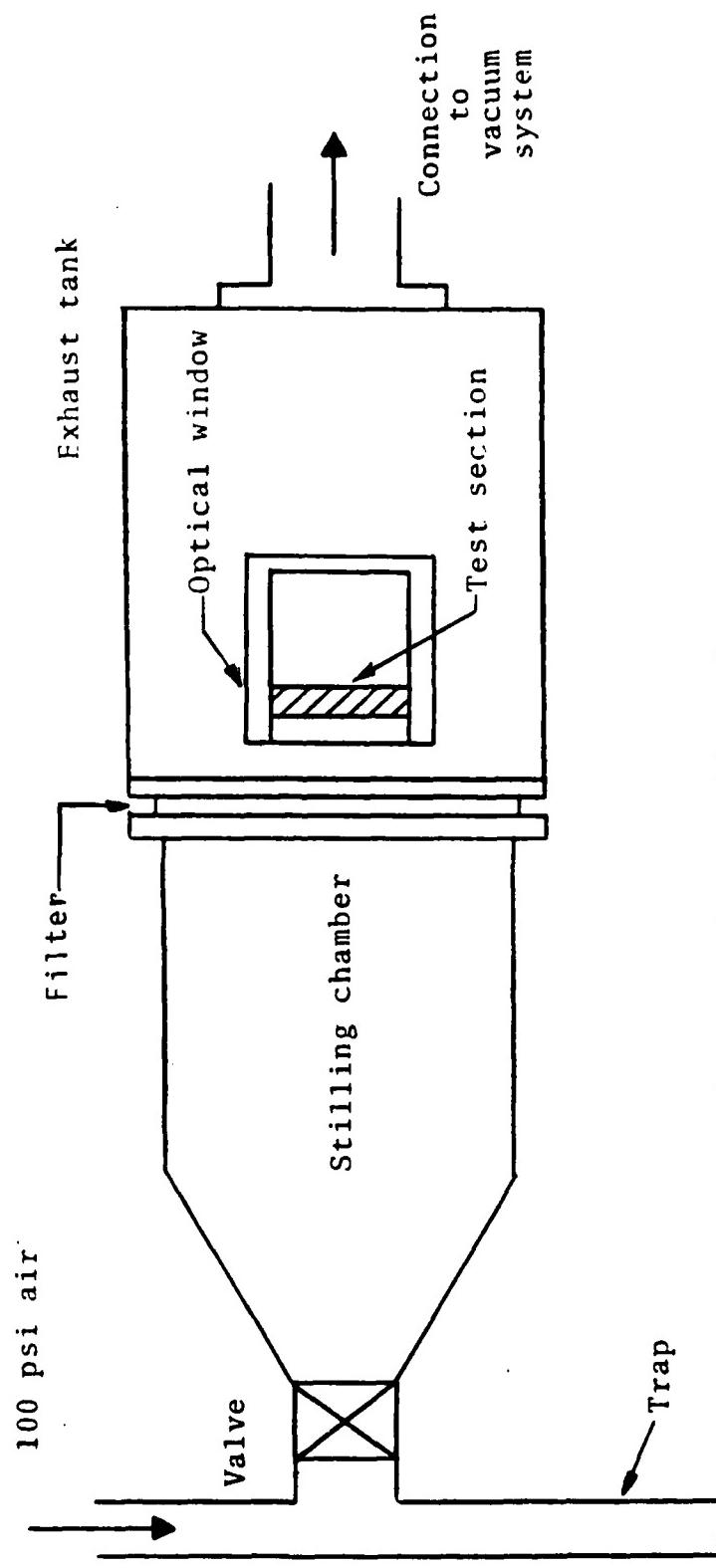
Figure 1. System Schematic

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paper-type filter and an external trap arrangement were included.

Test Section

The test section consisted of two parts as depicted in Figure 2. An outer section provided a track for the inner section to move within as well as allowing for the mounting of a load cell for thrust measurements. The inner test section held the nozzle bank. This section incorporated 1/2 inch thick plexiglass sides for the Schlieren pictures and roller bearings on the top and bottom to allow for movement with minimum friction. The two sections were attached together by means of a sheet of .01 inch thick mylar plastic which permitted a small amount of fore and aft travel while maintaining a pressure differential. Two metal plates with rubber gaskets were used to seal both the front and back ends of the test section for purposes of calibrating the transducers.

Nozzles

Three different sets of nozzles were studied. Each bank consisted of a pair of two-dimensional supersonic convergent-divergent nozzles with a design Mach number of 3.68. The only difference between the three involved the spacing between the nozzles and the side walls. Figure 3 depicts the nozzle shape and dimensions.

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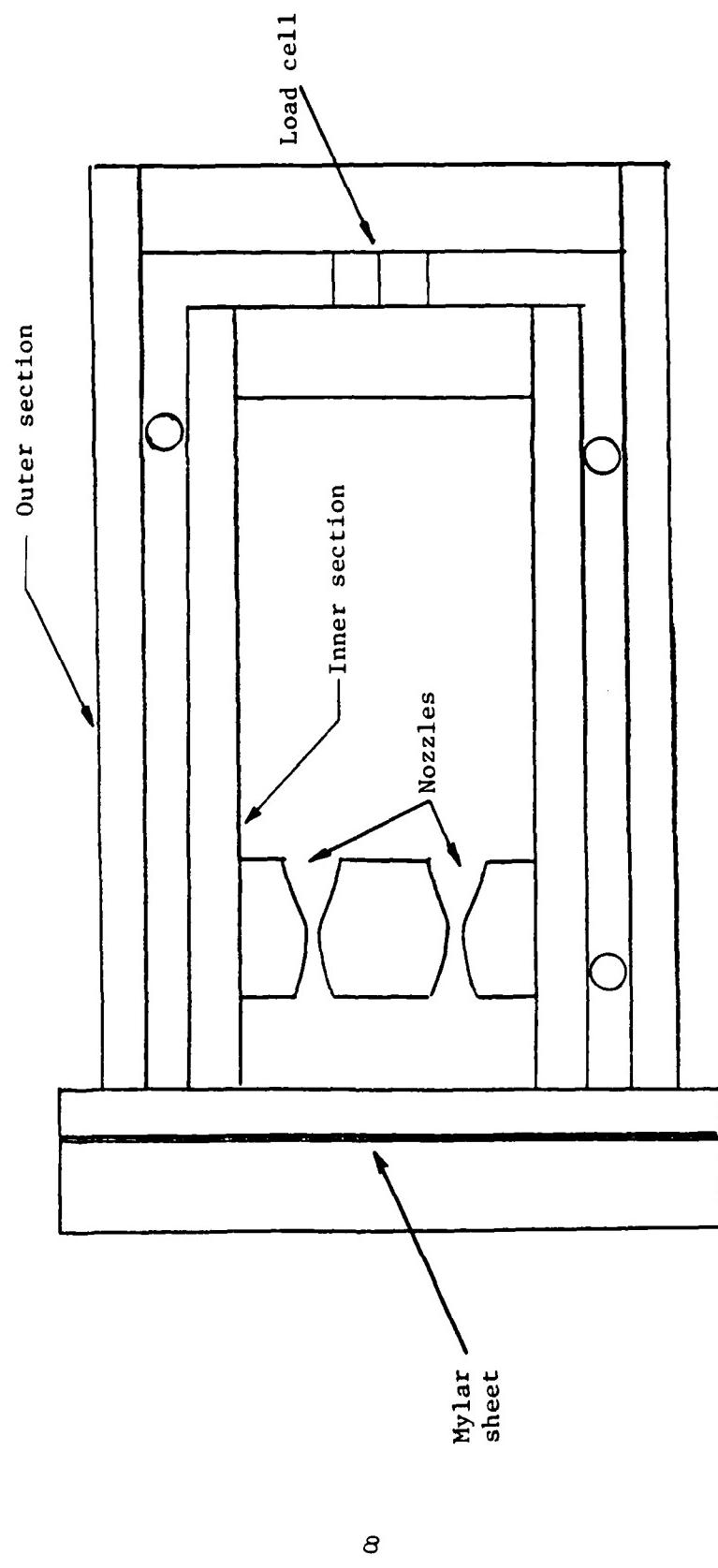
Figure 2. Test Section

8
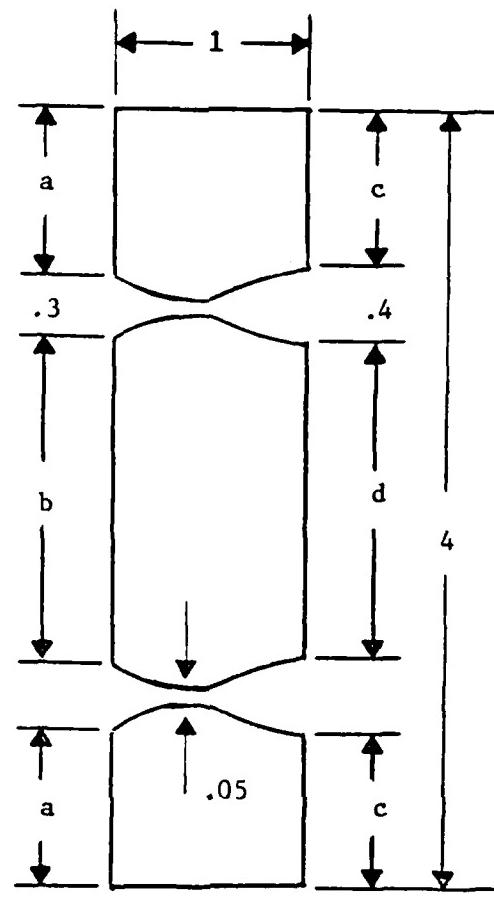
Nozzle Set	a	b	c	d
		(inches)		
1	1.55	.3	1.5	.2
2	1.2	1	1.15	.9
3	.85	1.7	.8	1.6

Figure 3. Nozzle Layout

Instrumentation

A total of six transducers were used to record data. Three channels were for three Endevco model 8506-5 piezoresistive pressure transducers that measured the exit plane pressure above, between, and below the nozzles (P_1, P_2, and P_3 respectively). These differential-type transducers were connected to a separate pump that generated a hard vacuum as a reference pressure. Channel 4 recorded downstream pressure data, P_A, from a CEC Type 4-353-0001 zero to 5 psia pressure transducer located on the large tank downstream of the test section. The fifth channel measured the upstream or stagnation pressure, P_C, using a CEC Type 1000-0002 zero to 100 psig pressure transducer. It was located just aft of the paper filter and forward of the test section. The final data channel was for information from the zero to 5000 lbf PCB Piezotronics model 208A05 force transducer.

In addition to the transducers, two mercury manometers were used to allow for easier runs and calibration. One was connected to the stilling chamber and a second to the large tank for measuring downstream pressures. Since the manometers had a 50 psi limit and the chamber pressure would approach twice that, a 200 inch Mercury pressure gauge allowed for calibration through the entire pressure range.

The six channels of data were recorded on six inch light sensitive paper using a model 906 Honeywell

visicorder. Each channel was wired separately using Honeywell M100-350 galvonometers plus shunt and series resistors as necessary. Table I lists the major test components.

Schlieren System

One of the objectives of the experiment was to study the nozzle exhaust in both the underexpanded and overexpanded regions. Pictures of the exhaust could be used to supplement the pressure data and allow one to see how the flow varied as the test environment changed. To study these unsteady flow conditions, a Schlieren system was devised that allowed for motion as well as still pictures. It incorporated Polaroid sheet film used in conjunction with a spark lamp for still pictures. Also, a steady light source was used for recording the entire run on either 16 mm film or on video tape using a video cassette recorder. Figure 4 depicts the Schlieren system used.

Table I   Test Instrumentation

Item	_Model No._	_Serial No._
Pressure transducer (P_1)	Endevco 8506-5	GK 81
Pressure transducer (P_2)	Endevco 8506-5	HF 07
Pressure transducer (P_3)	Endevco 8506-5	HE 99
Pressure transducer (P_A)	CEC 4-353-0001	5321
Pressure transducer (P_C)	CEC 1000-0002	7527
Force transducer	PCB 208A05	4340
Power supply	PCB 484B06	134
Power supply	Kepco KG25-02	A46362
Visicorder	Honeywell 906	9-8445
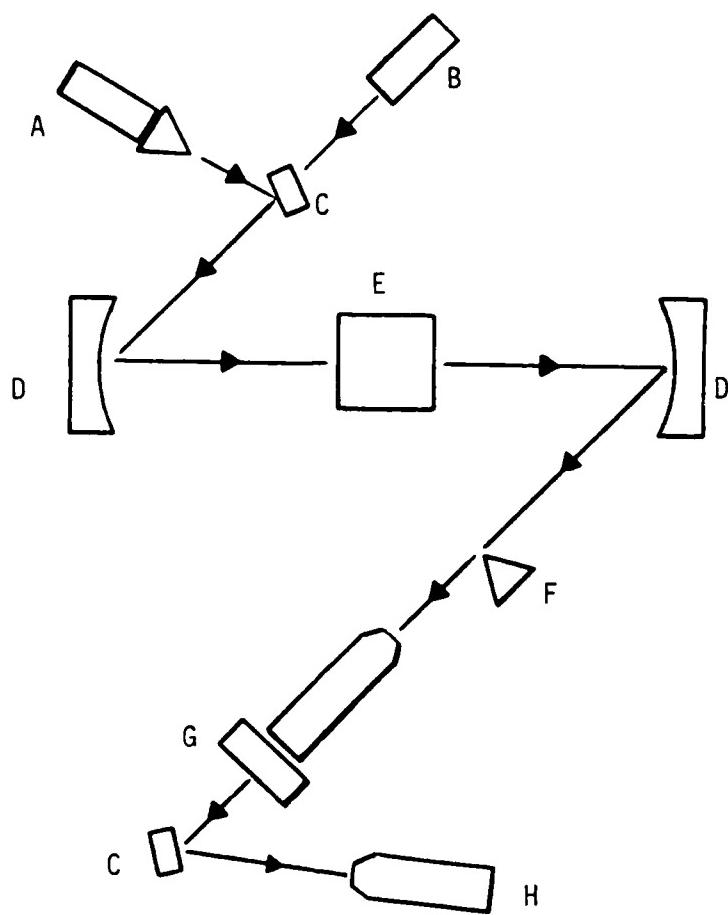
A. Steady light source (motion pictures)
B. Spark lamp (still photos)
C. Flat mirror
D. Concave mirror
E. Test section
F. Knife edge
G. Still camera (still photos)
H. Film or video camera (motion pictures)

Figure 4. Schlieren System

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III Experimental Procedure

Calibration

Each of the transducers was calibrated prior to the first test run and at the conclusion of the final run five weeks later. The second calibration sensitivities were found to be within 2.5 percent of the original values, thus lending credibility to the test results.

All five pressure transducers were calibrated in place on the apparatus. The three exit plane sensors were connected to a separate vacuum pump that established a reference pressure of approximately 0.01 psia. The main vacuum pumps were used to lower the vacuum-chamber pressure to values within the transducer's range above the reference pressure. These transducers would then generate a voltage corresponding approximately to absolute pressure. A digital voltmeter was used to record the voltage while a mercury manometer indicated the ambient pressure. The slope of the pressure versus voltage curve was used to determine the sensitivity of the transducer.

The chamber pressure transducer was calibrated in much the same way. With both the front and rear of the test section plugged to minimize leakage, the stilling chamber pressure was raised and regulated by means of a small air supply line attached to the stilling chamber. The resulting voltage output was measured at a series of pressures within

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the transducer's range. A pressure gauge was used for reading pressures above the limit of the 100 inch manometer. Since the pressure gauge agreed very closely with the manometer in the zero to 50 psig range it was assumed that the gauge was also accurate up to the maximum chamber pressure of approximately 100 psia. Calibration of the downstream or back pressure transducer was accomplished in a similar way by using the vacuum system to lower the pressure in the large tank. Voltage readings were tabulated at a number of approximately absolute, manometer pressure readings.

The load cell transducer proved to be the most difficult to calibrate. No adequate solution could be devised which would allow for calibration on the apparatus. Instead, the load cell and the bar to which it was mounted were removed from the apparatus and placed within a Baldwin Universal Testing Machine. Using this device, incremental loads could be applied to the cell and the corresponding output voltages recorded.

Test Procedure

The basic procedure on all test runs was the same. First, each of the air valves including the main valve into the stilling chamber were closed. All of the associated electronics were turned on, the excitation voltage for the pressure transducers was set to 10 volts DC, and the load

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cell power supply was adjusted to zero output voltage. The reference vacuum system for the pressure transducers was started and allowed to stabilize. Then, the two main vacuum pumps were used to establish the desired initial downstream conditions. Since on each run this downstream pressure would vary continuously, thus providing a changing overall pressure ratio, it was normal to establish the lowest starting back pressure possible. Due to small leaks within the system this initial value was limited to approximately 0.5 psia.

Once the initial conditions were established, the drive on the visicorder was engaged just before the main valve was opened. When the downstream pressure reached laboratory room ambient conditions, a valve within the vacuum system opened to prevent pressurizing the vacuum system and the run was terminated.

Data from the visicorder was then reduced with the aid of a micro computer. A program in BASIC was written to convert the deflections on the visicorder to either pressure or force, based on the sensitivity of the transducer. The use of the micro computer made for easy reduction and storage of the data.

IV   RESULTS AND DISCUSSION

Apparatus

An experimental apparatus was designed, built and tested for examining clustered nozzle performance. Ambient test pressures simulating altitudes up to 75,000 feet were possible. Chamber pressure could be maintained at 100 psig which allowed for pressure ratios of up to 200. The apparatus was instrumented with transducers which allowed for pressure information to be simultaneously gathered upstream, downstream and at the exit plane of the nozzles.

The situation of an ascending rocket is one where ambient pressure is decreasing from the relatively high sea level conditions to the near absolute vacuum of the upper atmosphere. This increasing ratio of chamber to ambient pressure is the reverse of what was generated within the apparatus. Ambient pressure in the experimental case was initially low and increased throughout the test run.

The equipment was capable of accommodating a variety of test sections thereby allowing for a wide range of differing geometries to be studied. In particular, different nozzle shapes and spacings along with aerodynamic shrouds of varying lengths and spacing could simulate any number of possible vehicle configurations. The apparatus provided good flexibility for this type of study. The geometry for the present study involved nozzles with a relatively large

expansion ratio, which limited the amount of time that the flow was underexpanded, and test section walls that acted as a very long shroud arrangement.

The effort to determine thrust through the use of a load cell proved impractical. The pressure-area force experienced by the cell was approximately 1600 lbf. On the other hand, the actual thrust of the nozzles was much less. A one-dimensional isentropic flow calculation using tabulated data (4) resulted in a theoretical thrust value of 32.4 lbf for the nozzle pair. This small force was impossible to distinguish from the larger pressure area force with the 5000 lbf transducer that was used.

Experimental Results

The pressure fields within the base region of three nozzle sets were established by direct measurement. This information was tabulated and is presented graphically in the Appendix. Actual pressure-time histories are plotted for the three cases in Figures A-1 through A-6. Pressure ratio is depicted versus time in Figure A-7. Additionally the base-pressure distribution for each nozzle set is presented for three different altitudes in Figures A-8 through A-10. Lastly, pressure non-dimensionalized by the ambient pressure is depicted against pressure ratio for the three nozzle sets in Figures A-11 through A-16.

The Schlieren system was used to take both still photos

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and film of each nozzle set. Figure 5, which is typical of the photographs, shows nozzle set three operating in the underexpanded and overexpanded flow regions. Due to the nature of the mirrors used in the system the images on the photos and film are inverted. The top exit plane pressure, P_1, is located at the bottom of the pictures and so forth. To supplement the pressure data several runs with each nozzle set were filmed.

Data from the pressure transducers was recorded with the visicorder for a number of test runs for each nozzle set. Repeatability was good throughout the experiment. At each point where an abrupt change of flow conditions was encountered additional runs with initial ambient pressure both above and below where the phenomenon occurred were accomplished. This procedure of using different starting back pressures indicated there were virtually no prior history effects involved in this experiment. That is, the changes of flow conditions occurred at the same pressure ratios regardless of what the starting condition was. The vacuum pump capacity was not adequate to check for hysterisis in the pressure ratio for flow condition changes by increasing the pressure ratio during the run.

Nozzle Set 1

Nozzle set one has the smallest spacing between the nozzles of the three sets (Fig. 3). From the film of this

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a. Underexpanded; PR=106

b. Overexpanded; PR=32

Fig 5. Schlieren Photographs of Nozzle Set 3

FIG. 6
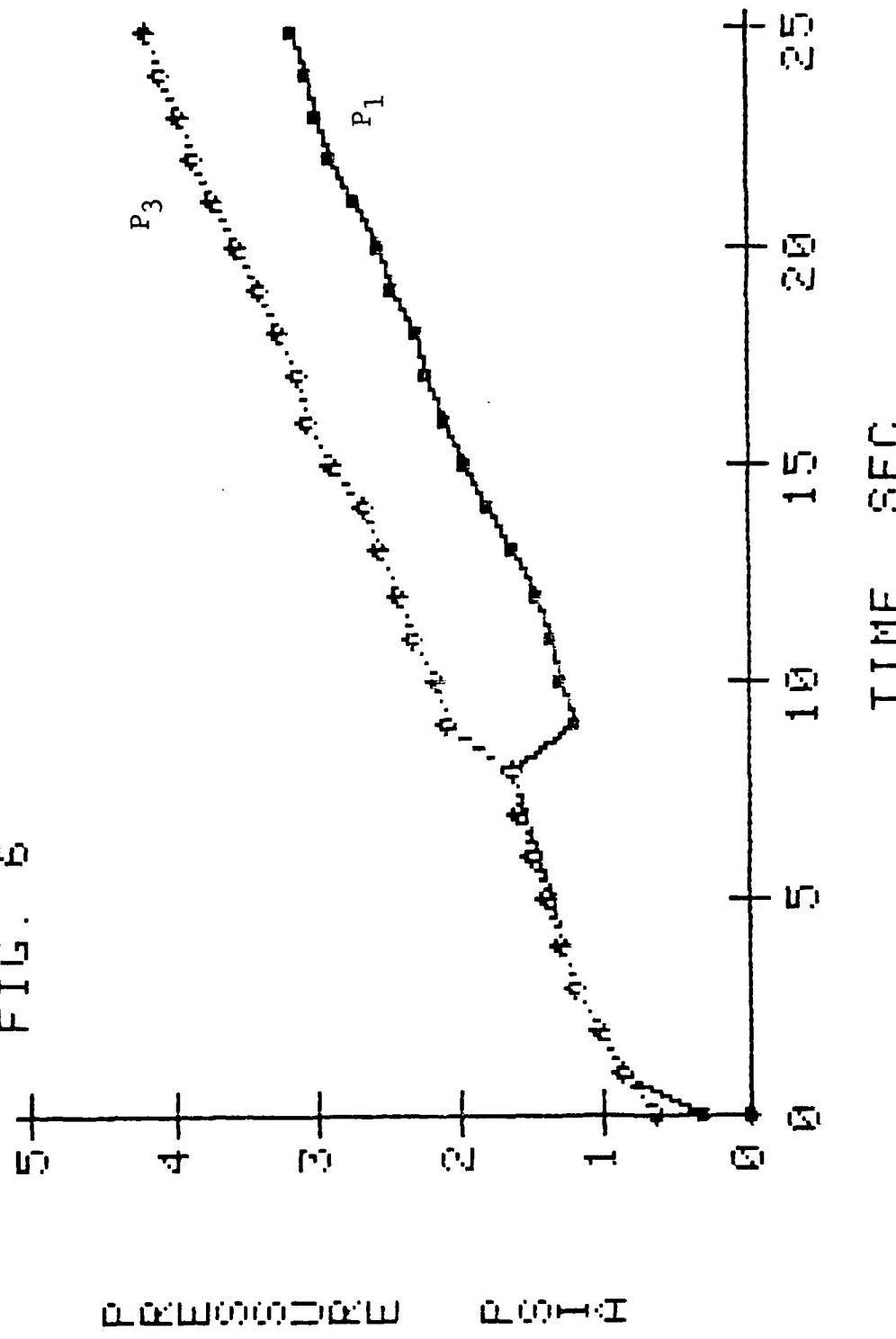
Fig 6. P_1 and P_3 vs Time for Nozzle Set 1

FIG. 7

TIME SEC
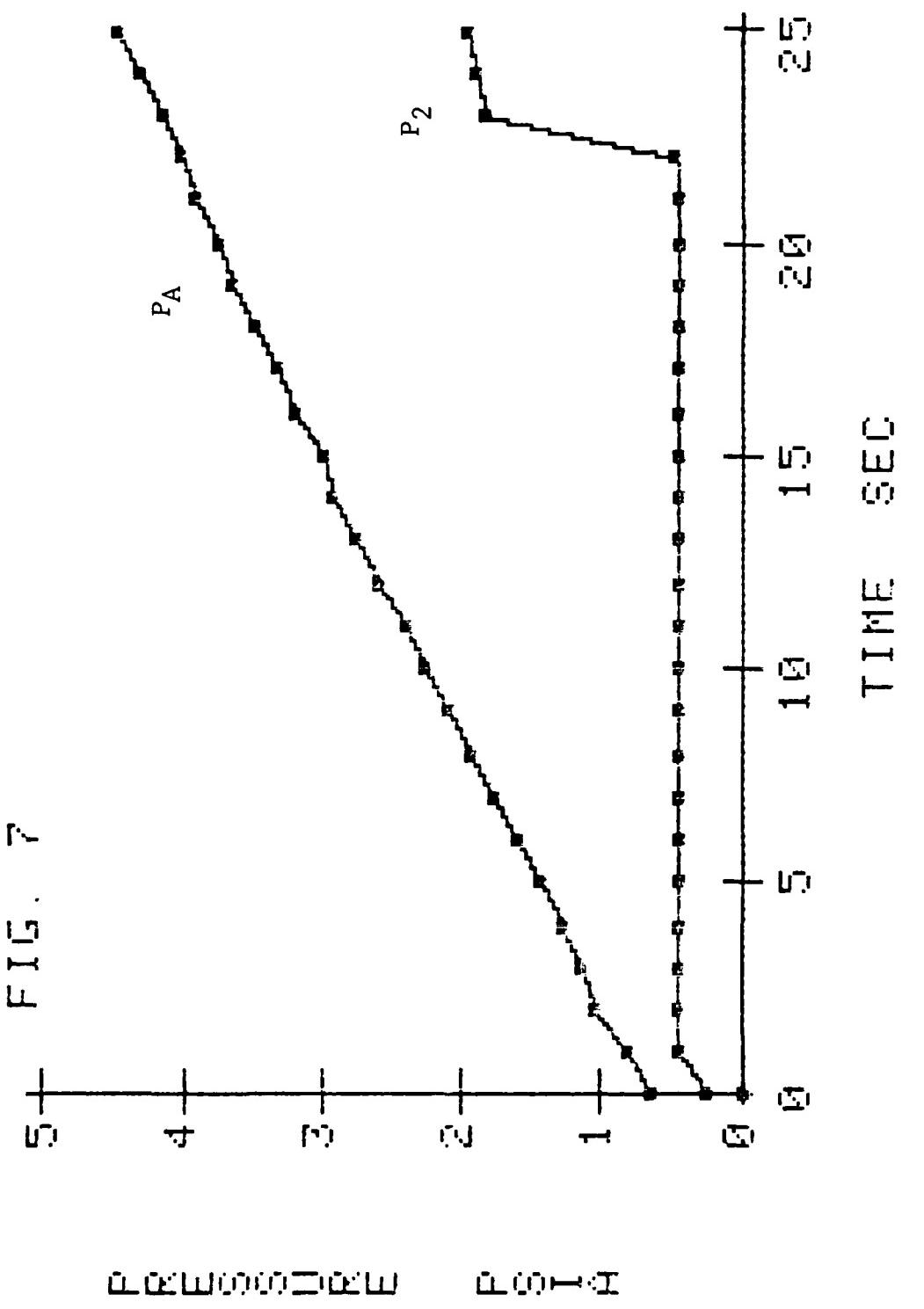
Fig 7. P_2 and P_A vs. Time for Nozzle Set 1

23

a.   Underexpanded; PR=95

b.   Overexpanded; PR=20

Fig 8.   Schlieren Photographs of Nozzle Set 1

The base pressure at the center of the configuration, P_2, was less than that at the top, P_1, or bottom, P_3, of the set and was also less than back pressure, P_A. This pattern fluctuated somewhat with altitude but was present at all three simulated altitudes.

Nozzle Set 2

This configuration had increased spacing in comparison to the first (Fig. 3). As indicated by the films, the flow started initially straight with the two jets connected and touching both the upper and lower test section walls. At the 3 second point, PR=87, the flow consistently shifted upward toward the P_1 location. This can be seen on Figure A-3 where P_1 and P_3 initially rose and then, at the point the flow bends, P_3 jumped upward and then followed the rising back pressure. P_1 remained constant until a point after the flow shift and then began to increase with rising back pressure.

P_2 made an initial large jump in pressure and remained nearly constant throughout the run (Fig A-4). This is surprising because the film showed that at 7 seconds into the run, PR=56, the two flows appeaed to separate. At that point P_2 showed no reaction.

The initial large increase in the center pressure is reflected in the base pressure diagrams (Fig. A-8 to A-10). This indicates that the P_2 value was well above the back

pressure at each of the simulated altitudes.

Nozzle Set 3

Nozzle set three had the widest spacing with the two nozzles close to the upper and lower walls. In this configuration the two nozzles were centered in the upper and lower halves of the flow channel. The top and bottom pressures, P_1 and P_3, initially decreased slightly and then remained constant until about 8 seconds, PR=50, into the run. At that time both pressures showed a sharp increase after which they followed the increase of the back pressure.

The films showed that the two jets were at first operating connected to each other and attached to the upper and lower walls. At the 8 second point they apparently separated and simultaneously shifted downward. The center pressure responded much as in set two: an initial increase, although less than that of set two, was followed by near constant pressure. The base pressure distribution for nozzle set three is similar to those of set two but less consistent with simulated altitude (Fig. A-8 to A-10).

Discussion

The behavior of the exhaust of a single supersonic nozzle in both underexpanded and overexpanded flow is well established (3:410-411). This study suggests that when two nozzles operate in close proximity additional complications

to the flow arise. Common to all three nozzle sets was the tendency for the flows to begin with the two jets interconnected. Optimum expansion for the nozzle design under consideration occurs at a pressure altitude of 60,000 feet which corresponded to 3 seconds into a test run. Flow after the 3 second point was overexpanded and prior to it underexpanded. This short period spent in the underexpanded region established the initial flow conditions. The spreading of the jets that occured within the underexpansion region caused the two jets to interact. The center region became isolated from outside effects for some period of time (Figs. 7, A-2, A-4, A-6).

The investigation into the prior history effects indicated some interesting results. Even when the starting back pressure was higher; such that the conditions were definitely overexpanded, the flows tended to begin combined. From the earlier work by Lester (5), this spreading and interaction of the plumes did not occur in the overexpanded region with non-two-dimensional nozzles. This suggests some definite differences between the two-dimensional and non-two-dimensional cases even when operating with similar pressure ratios. Further investigations should incorporate both types of nozzles.

In nozzle set one, P_2 dropped initially and then was constant (Figs. 7, A-2). In this first set because of the small space between nozzles the two jets intersect a short

distance downstream (Fig. 8a). If at this distance an effective nozzle exit area is established, an effective nozzle exit pressure can be calculated. Using tables (4) for an effective area ratio of 10.66, as opposed to the actual nozzle area ratio of 8; this new exit pressure would be 0.60 psia instead of 1.01 psia at the physical exit plane. The center pressure is constant at a value of 0.45 psia. This rough equivalence of the measured center pressure and a rough theoretical effective exit pressure suggests that, in the case of nozzle set one, each nozzle may be acting as an equivalent nozzle of larger expansion ratio and dictating the value of P_2 isolated between the jets.

In both nozzle sets two and three, P_2 rose and then remained virtually constant. This situation of a cluster center pressure considerably larger than back pressure is consistent with Goethert's early work with non-two-dimensional nozzles. "This pressure difference is necessary since otherwise the exhaust gases in the mixing zone of the jet boundaries could not penetrate downstream into the high pressure area behind the intersections of the jets" (1:12). In many of the still photos of set two a strong recirculation back toward the base area existed between the two jets. This reverse flow was also evident in nozzle set three but to a lesser degree. This may correspond to the fact that P_2 increased initially in set three (Fig. A-6) but with not as large an increase as in set

two (Fig. A-4). As indicated above, nozzle set one proved different with an initial decrease in P_2 followed by constant behavior.

A second common characteristic among the three nozzle sets was the flow shift that occurs in the 3 to 7 second period. Having entered the overexpanded regime it appears that as the overexpansion became greater the combined jets became unstable in the shroud enclosure and attach to either the top or bottom walls. In set one the pattern was random, but set two consistently attached to the upper surface and set three to the lower. Prior to this bending of the flow, both nozzle sets two and three were connected to the top and bottom walls relatively close to the exit plane. As the flow shifted it disengaged from one wall but remained attached to the other; however, the point of attachment shifted farther downstream. Apparently in each of these later cases there is some asymmetry present which causes the unstable jet pattern to always bend in the same direction.

The reason for the initial decrease in both P_1 and P_3 for nozzle set three (Fig. A-5) may be similar to the argument offered for P_2 in nozzle set one. Set three is symmetric about a horizontal centerplane. If each nozzle initially acted as an effective nozzle with an exit area equal to one half of the total test section height the resulting exit pressure could establish the initial P_1 and P_3 values. The exit pressure for an expansion ratio of 40

(2"/.05") is 0.12 psia which is similar to that measured for P_1 and P_3, with values of 0.08 and 0.14 psia, respectively. On certain of the photographs an additional boundary line appears beyond the normal shocks and waves that were anticipated. It is possible that this boundary acted as a side wall causing an effective area increase beyond the actual exit plane.

In the case of nozzle set one the jets were so far from the walls that there was no period where P_1 and P_3 were constant as the flow had not interacted with the walls (Fig. 8a). Both pressures followed the rising back pressure (Figs. 6, A-1). Nozzle set two showed an initial increase in both P_1 and P_3 followed by a short constant period. The reason why in this case these pressures rose remains uncertain. In all of the configurations once this upward or downward flow shift had occurred both P_1 and P_3 followed the increasing back pressure.

Overexpanded flow is characterized by a contracting of the flow downstream. As the degree of overexpansion increases this tendency is magnified. With each nozzle set some point in the test run was reached where the flow was sufficiently overexpanded to cause the two jets to separate from each other in the region near the exit plane. This point occured near 8 seconds, PR=50, into the run for both sets two and three. After the two jets separated it was surprising that the center pressure continued to remain

constant rather than shift toward the back pressure. The reason became apparent in the still photos. In both cases even though the flows have definitely separated near the exit plane there was still interaction farther downstream. Figure 5 shows for nozzle set three (a) the two jets interconnected by gasdynamic expansion prior to the 8 second point and (b) the two jets disconnected up close but merging farther downstream. This continued interaction was sufficient to keep P_2 isolated throughout the run for nozzle set two and until late in the run for set three.

In nozzle set one the point at which the jets disconnected from each other was consistently 22 seconds, PR=22, into the run. At this point P_2 quickly increased to a value less than the back pressure (Figs. 7, A-2) and continued to increase at the same rate that the back pressure was increasing. In overexpanded flow for an isolated free jet an oblique shock pattern is present to bring the nozzle exit pressure up to the local ambient pressure. The P_2 value for nozzle set one after the jets separate apparently varied with the strength of the oblique shock pattern which in turn varied with the degree of overexpansion. Further examination of this flow situation is needed to determine if non-two-dimensional flow systems behave similarly.

The rationale for exploring both clustered nozzles and shrouds lies both in an explanation for and a potential to

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exploit increased nozzle performance. From equation (1) any added performance must come from the pressure-area term or the momentum flux term.

$$T = mU_E/g_c + (P_E - P_A)A_E \qquad (1)$$

This study suggests the possibility that each term may be affected by the clustering of nozzles and the use of an adjacent shroud. The region of high pressure between the two nozzles in both sets two and three could provide an additional pressure-area term acting over a portion of the base region. This potential increase becomes more prominent at higher simulated altitudes due to the constant P_2 and decreasing P_A (Fig. 8 to 10).

The concept of each nozzle at times acting as an effective nozzle of a larger expansion ratio provides the potential to also effect the momentum thrust term. In the case of nozzle set three where the pressure data suggests this may occur, the increase exit velocity resulting from continued expansion within the shroud to a larger effective nozzle expansion ratio would theoretically produce a thrust increase on the order of eight percent. The potential of this gas dynamic effect to augment performance is of interest and should be examined further.

V CONCLUSIONS

The apparatus and associated instrumentation were designed, constructed and tested during the project. Additionally, the pressure fields of three sets of two-dimensional nozzles were studied under a range of test conditions. Results of these tests lead to the following conclusions:

1. The equipment is suitable for examining the pressure distribution and flow behavior in the base region for a variety of clustered-nozzle configurations.

2. The exhausts of neighboring nozzles tend to interact with each other at certain pressure ratios. This interaction generates markedly different pressure fields than are observed with no interaction.

3. The potential for thrust augmentation is heavily geometry dependent. With the proper spacing performance may be affected both through the gas dynamics of the flow and through the appearance of additional pressure area terms.

VI RECOMMENDATIONS

The following recommendations are suggested for continuation of this work on clustered nozzles:

1. Different nozzles be constructed having a lower exit to throat area ratio to allow for more data from the underexpanded region. Additionally non-two-dimensional configurations should be included.

2. An adjustable or removable shroud be incorporated into the test section to study the effects of shroud configuration and its interaction with the jet flow on thrust augmentation.

3. A more sensitive means of measuring thrust should be developed to enhance future studies. Also the hardware associated with this measurement should be constructed such that there is a minimum amount of influence on the flow.

4. One of AFIT's data acquisition systems should be adapted to this system for more complete data taking and reduction.

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Appendix

FIG. Ḣ-1
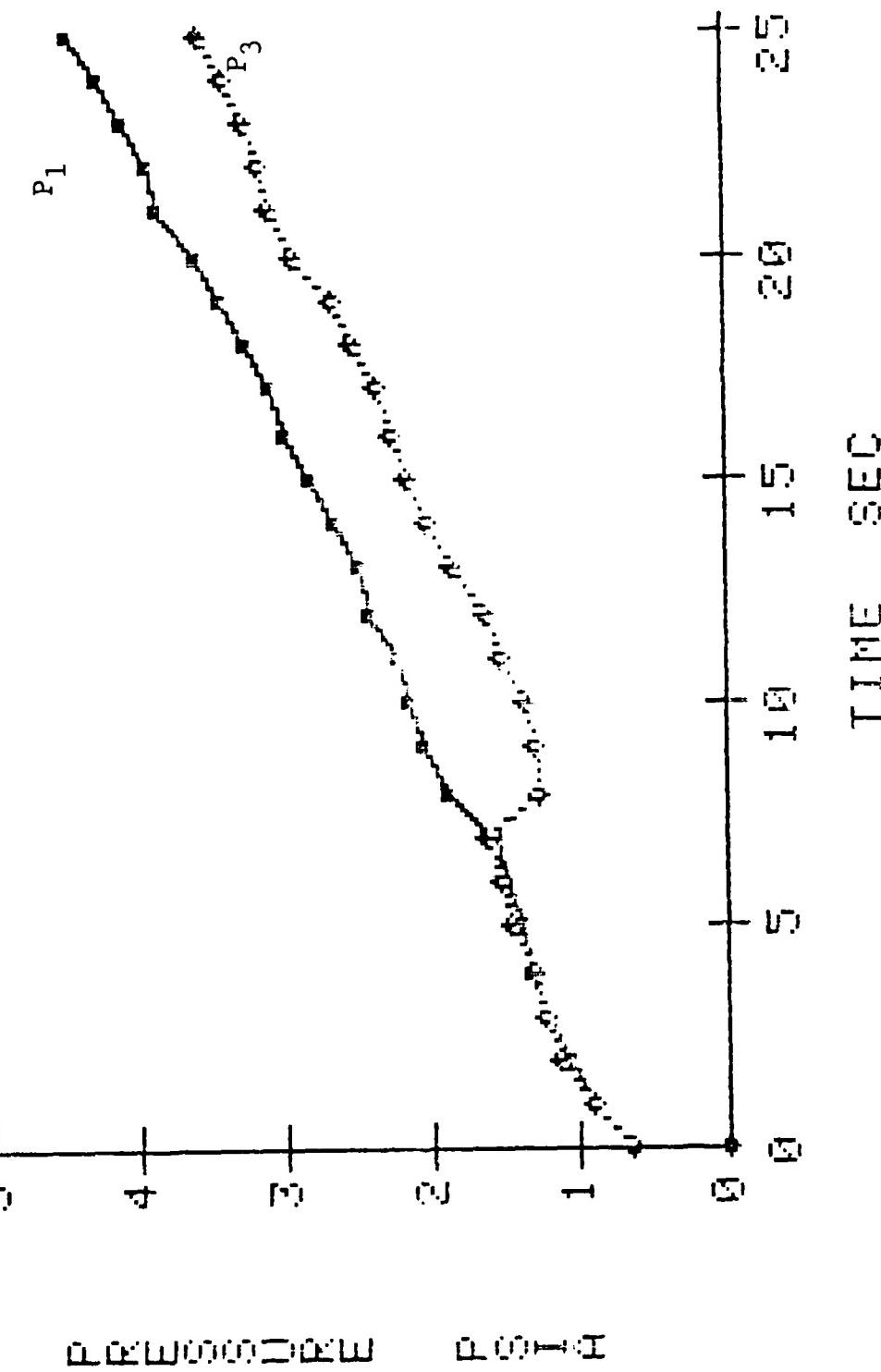
Fig A-1. P₁ and P₃ vs Time for Nozzle Set 1

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FIG. A-2

TIME SEC
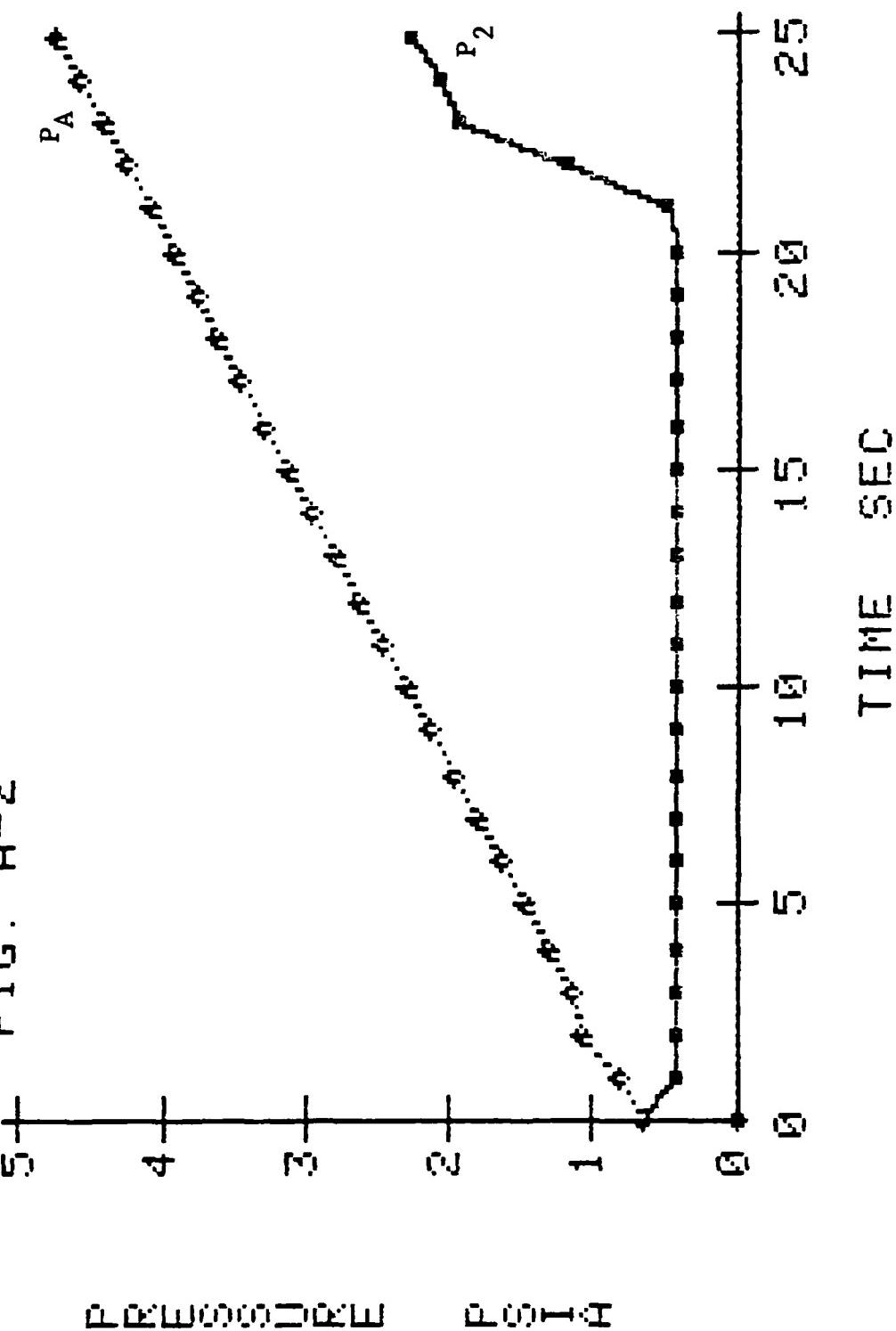
Fig A-2. P_2 and P_A vs Time for Nozzle Set 1

FIG. A-3

TIME SEC

Fig A-3. P_1 and P_3 vs Time for Nozzle Set 2

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FIG. A-4

P₂

P_A

TIME SEC
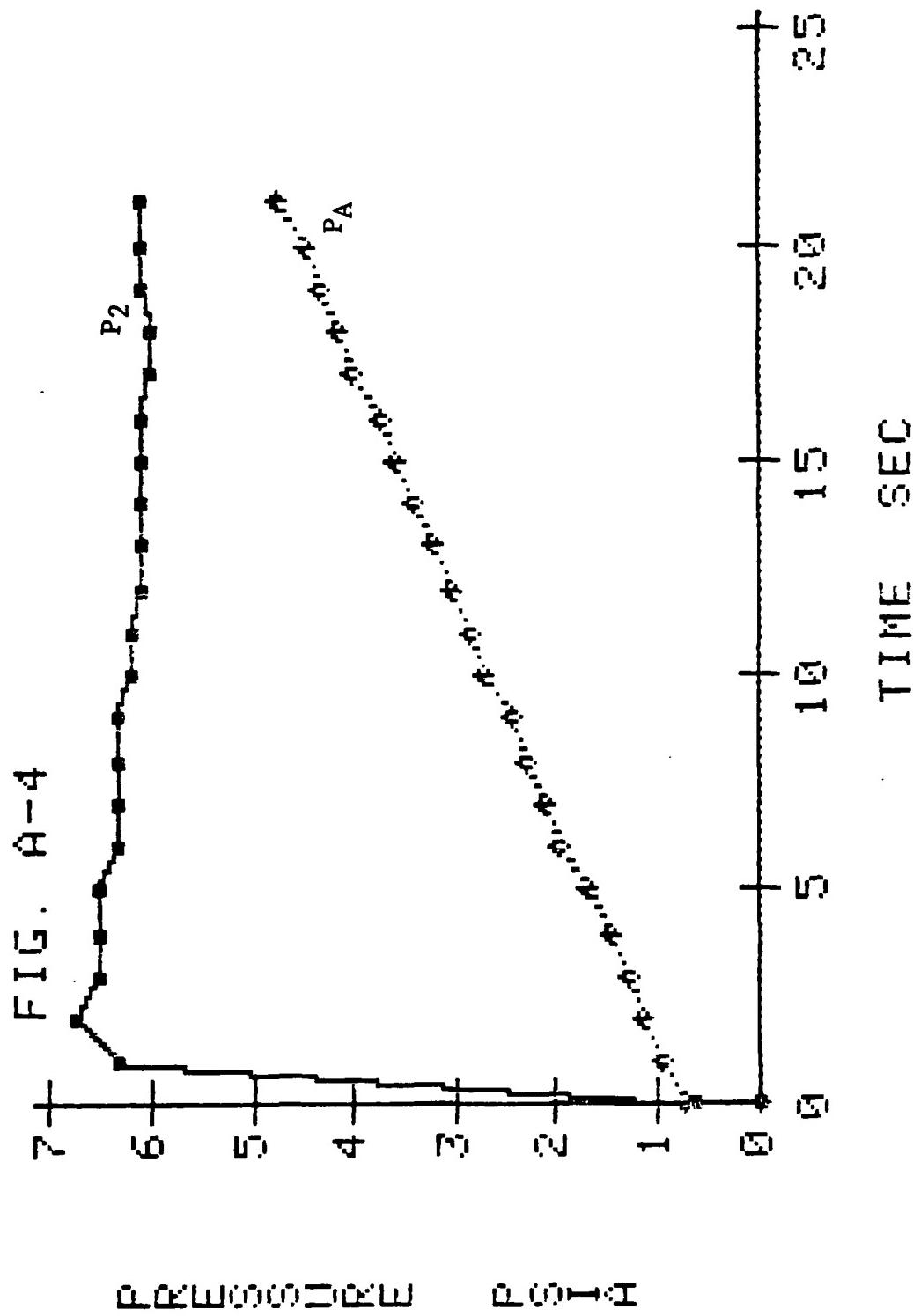
PRESSURE PSIA

Fig A-4. P_2 and P_A vs Time for Nozzle Set 2

40
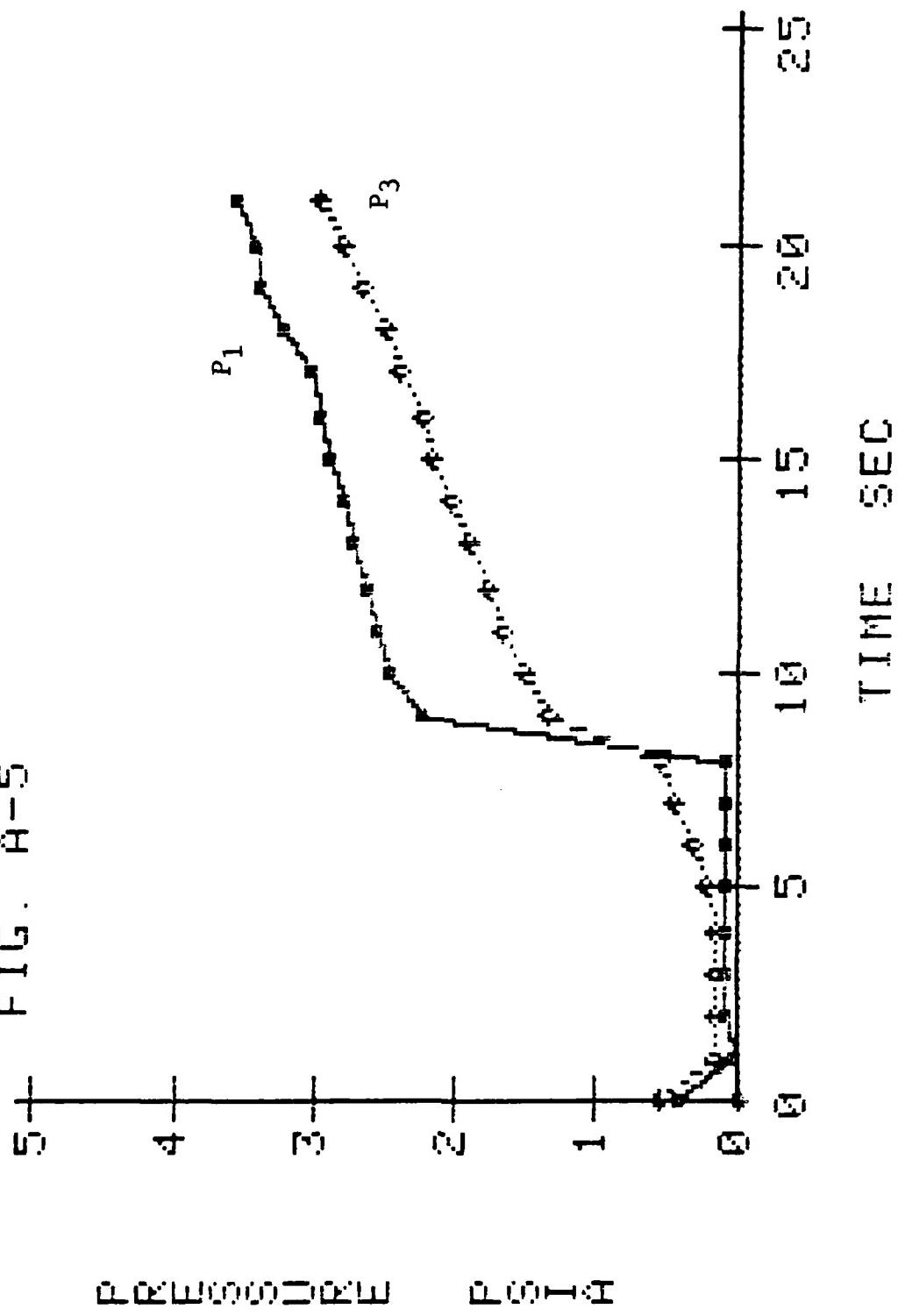
FIG. A-5

Fig A-5. P_1 and P_3 vs Time for Nozzle Set 3

41
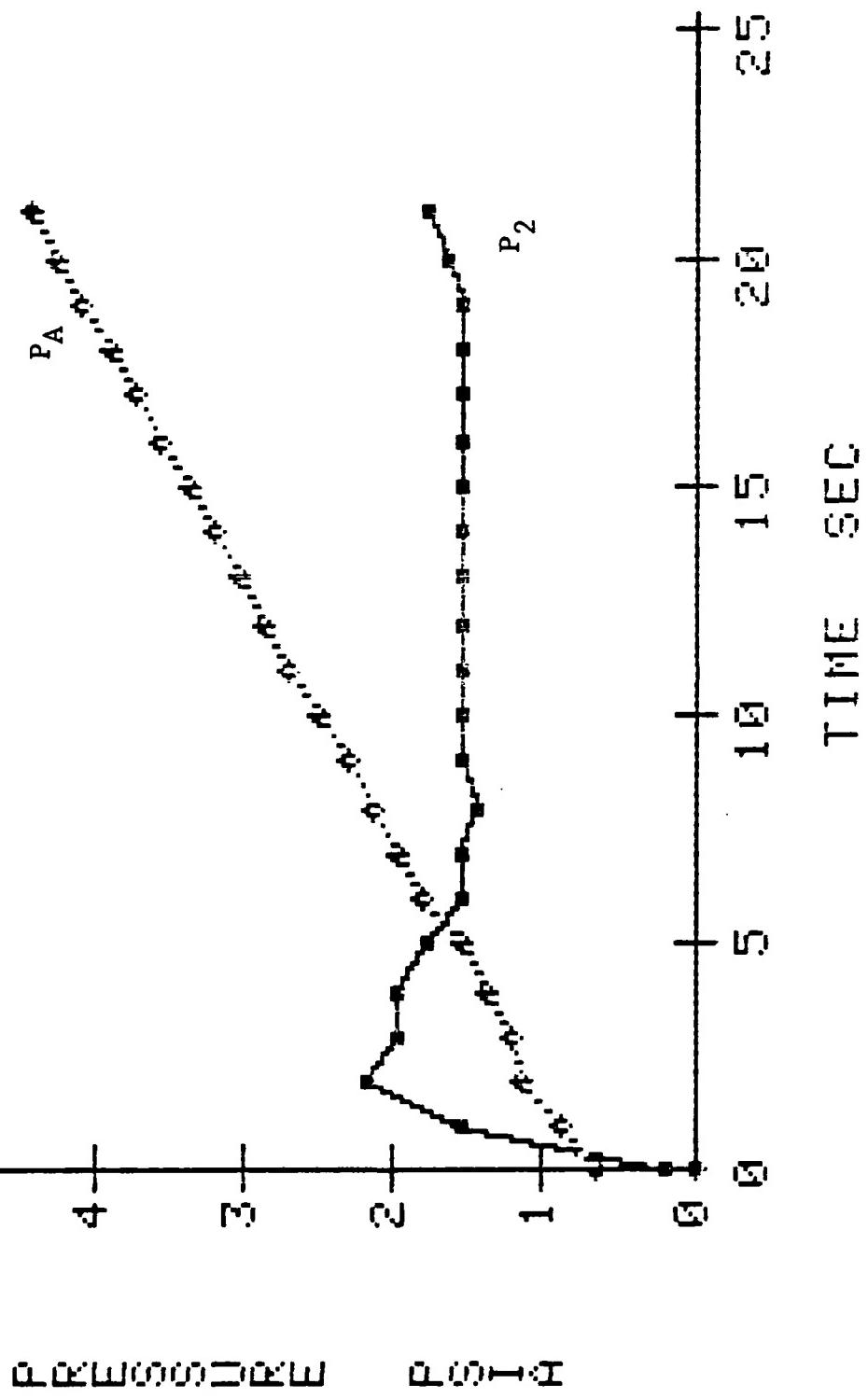
FIG. A-6

Fig A-6. P_2 and P_A vs Time for Nozzle Set 3
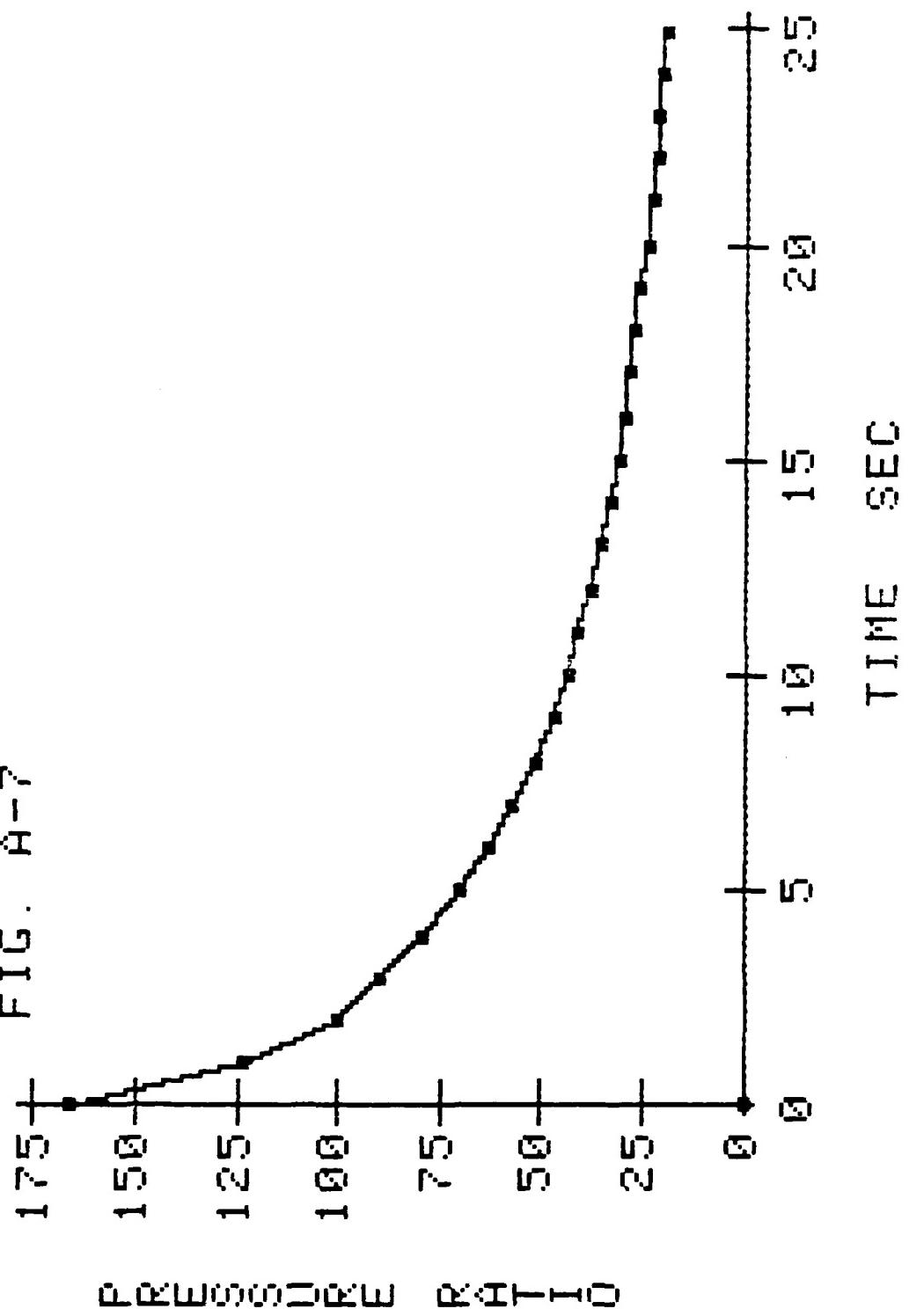
Fig A-7. Pressure Ratio vs Time

FIG. A-8
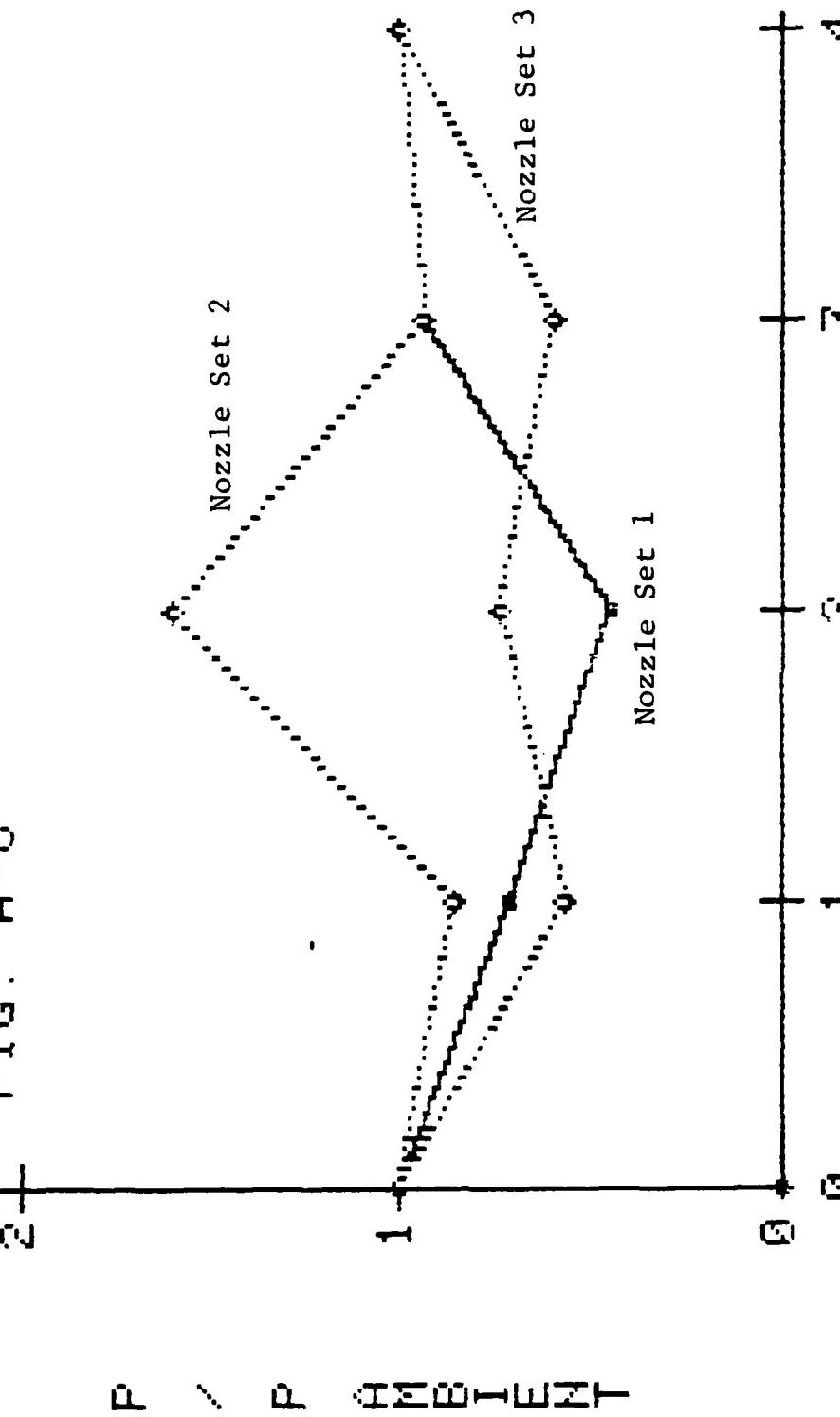
PRESSURE POSITION

Fig A-8. Base Pressure Distribution at 30,000 ft.

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FIG. A-9

PRESSURE POSITION

P / P AMBIENT
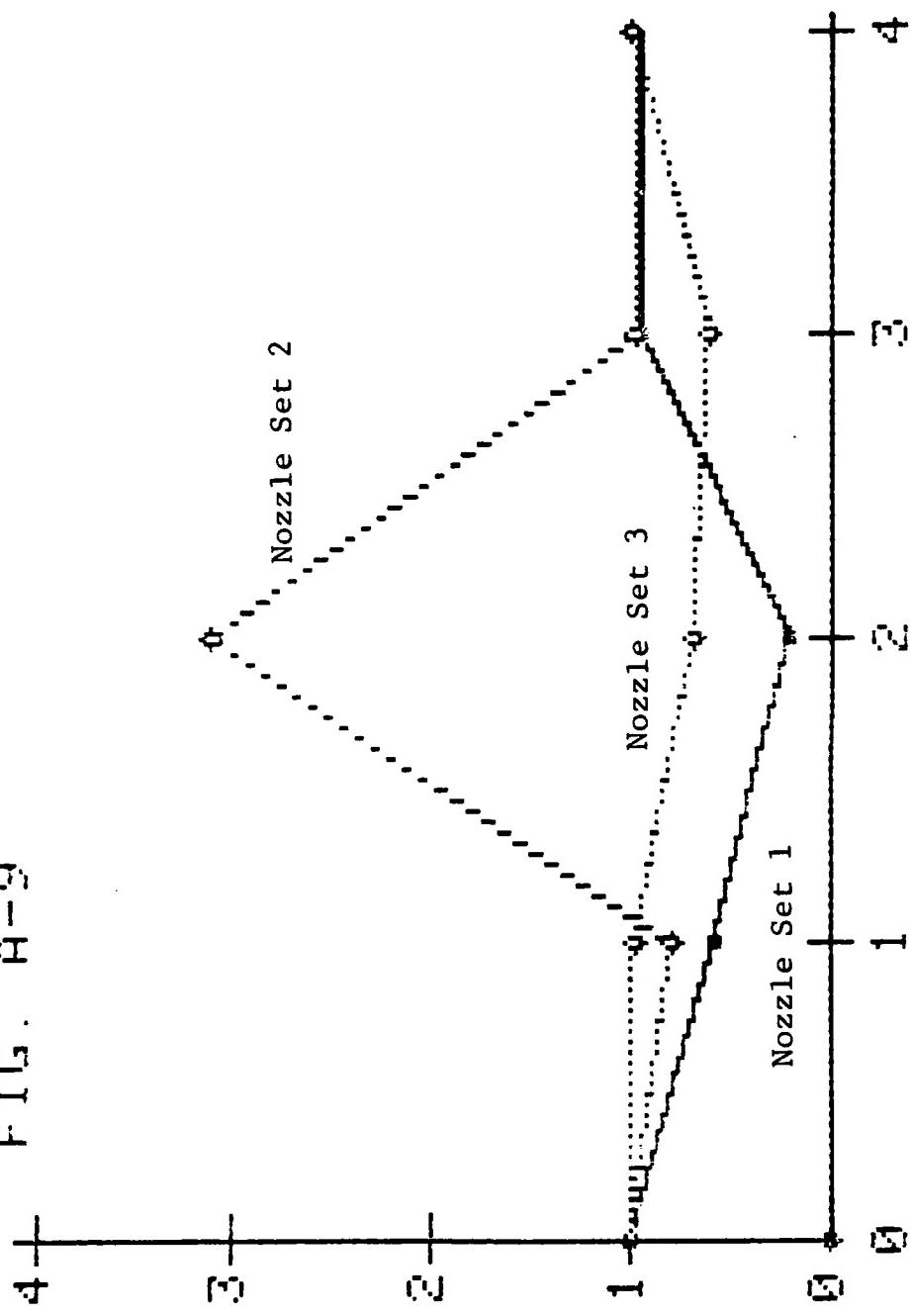
Nozzle Set 1

Nozzle Set 2

Nozzle Set 3

Fig A-9. Base Pressure Distribution at 44,000 ft.

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FIG. A-10

Nozzle Set 2

Nozzle Set 3
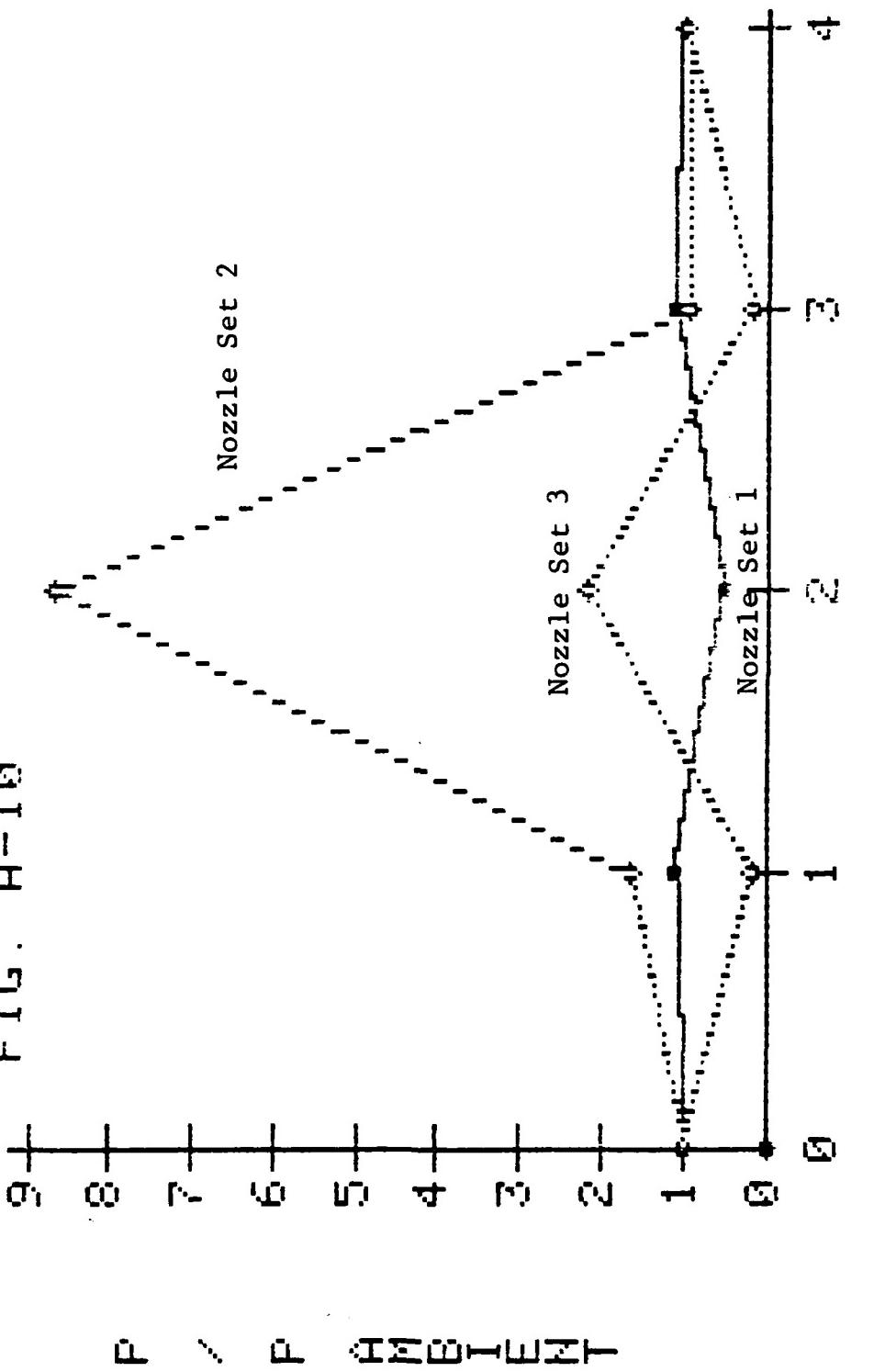
Nozzle Set 1

PRESSURE POSITION

Fig A-10. Base Pressure Distribution at 65,000 ft.

FIG. A-11
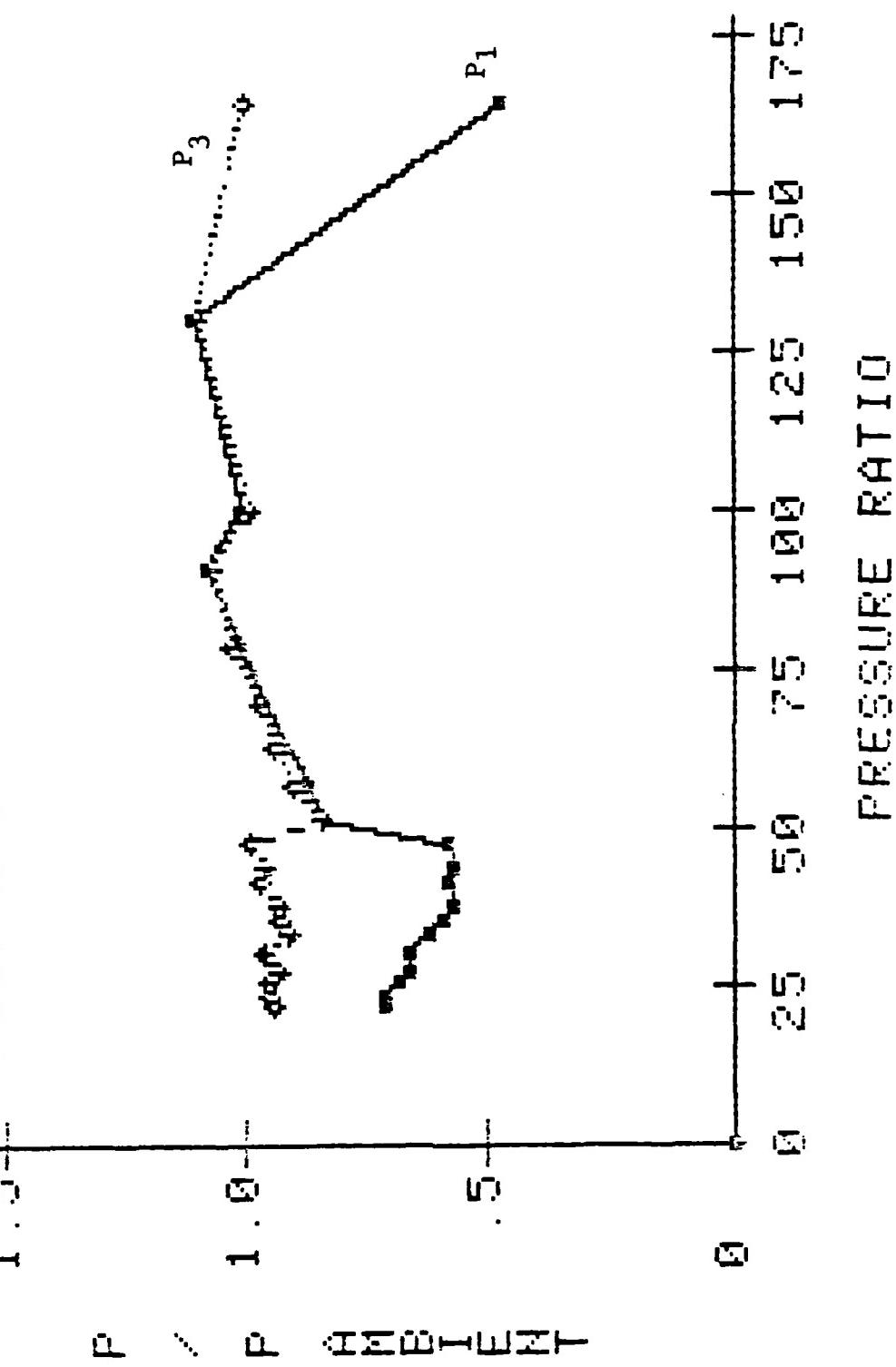
Fig A-11. P_1/P_A and P_3/P_A vs PR for Nozzle Set 1

FIG. A-12
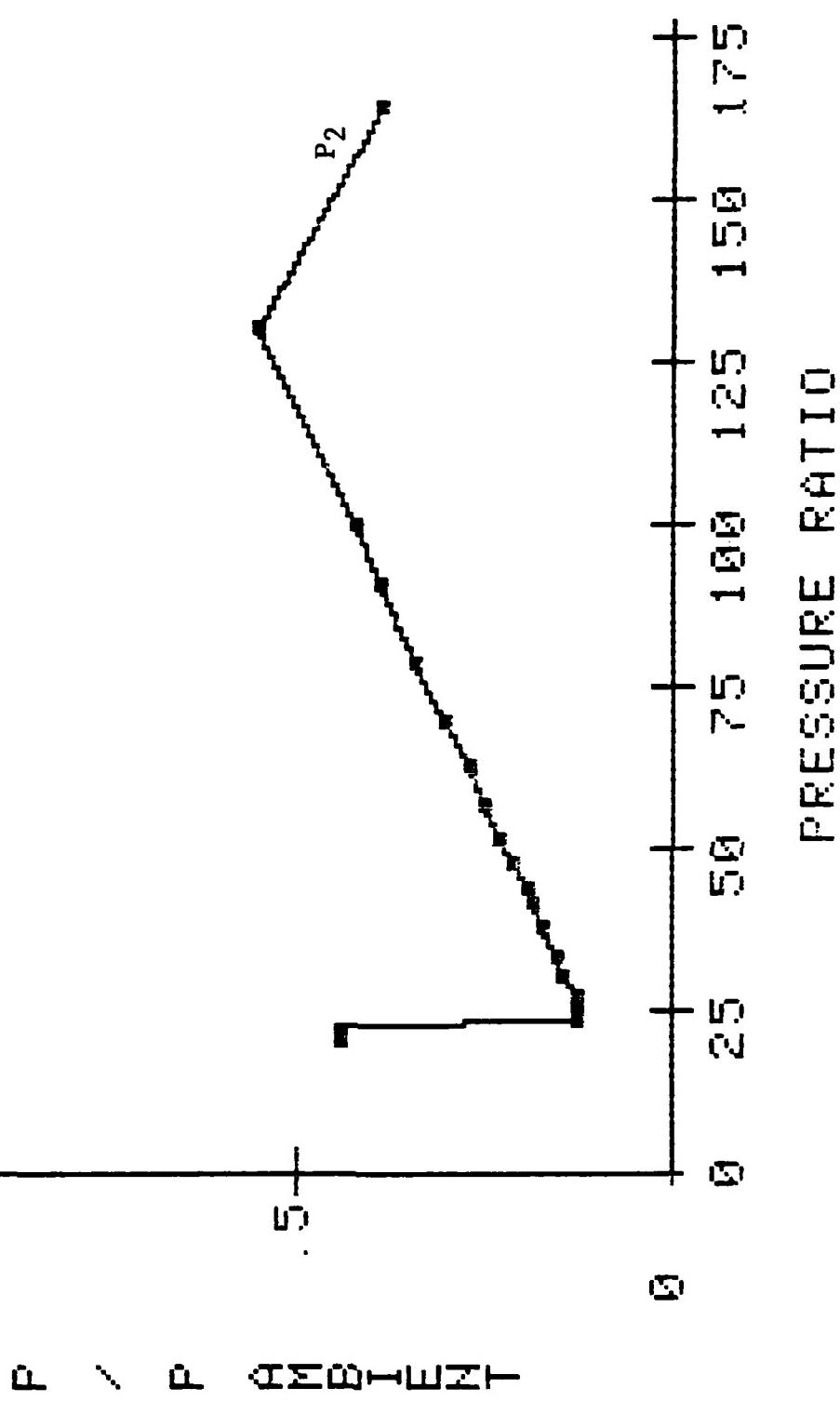
Fig A-12. P_2/P_A vs PR for Nozzle Set 1

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FIG. A-13

PRESSURE RATIO
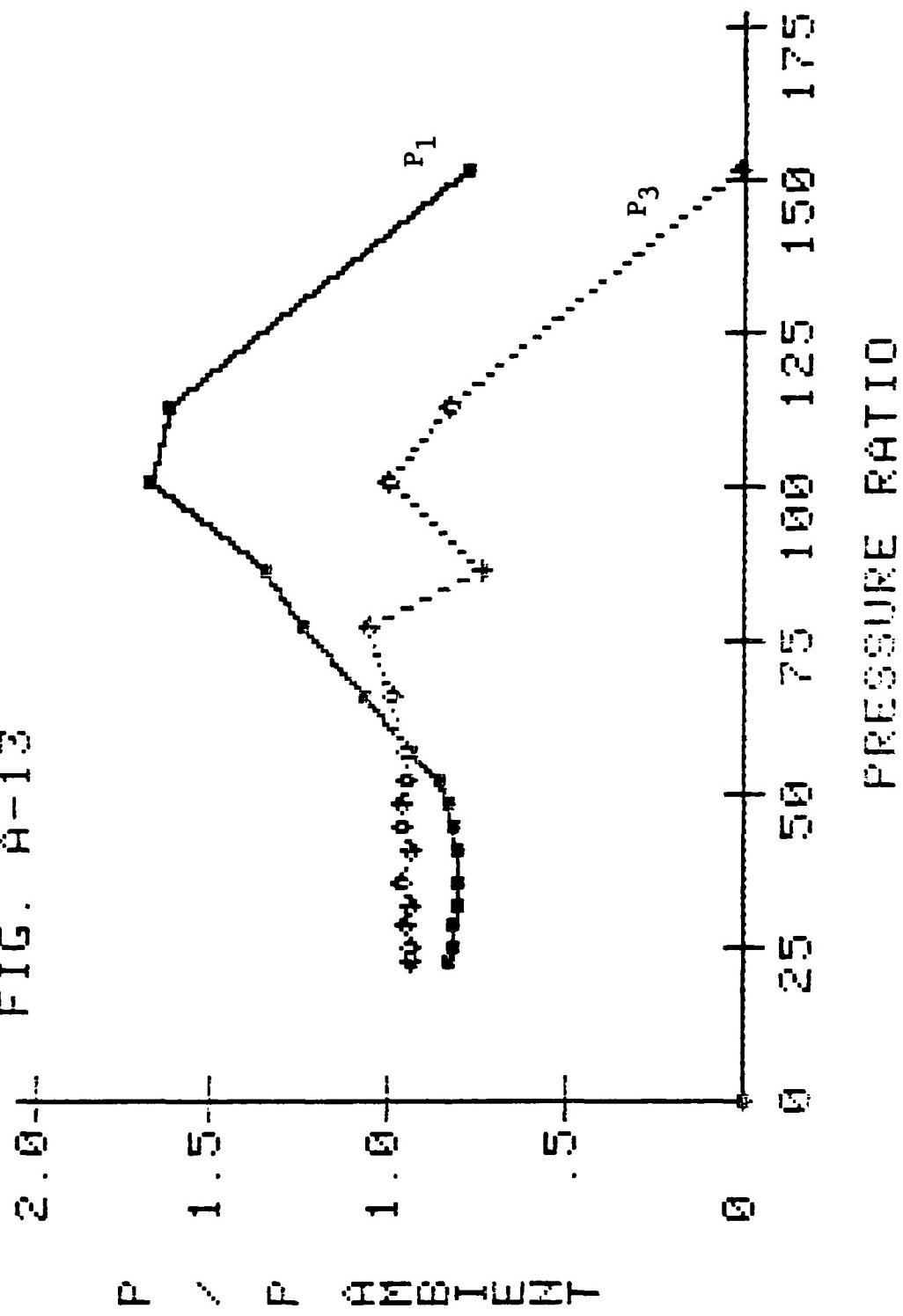
Fig A-13. P_1/P_A and P_3/P_A vs PR for Nozzle Set 2

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FIG. A-14

Fig A-14. P_2/P_A vs PR for Nozzle Set 2

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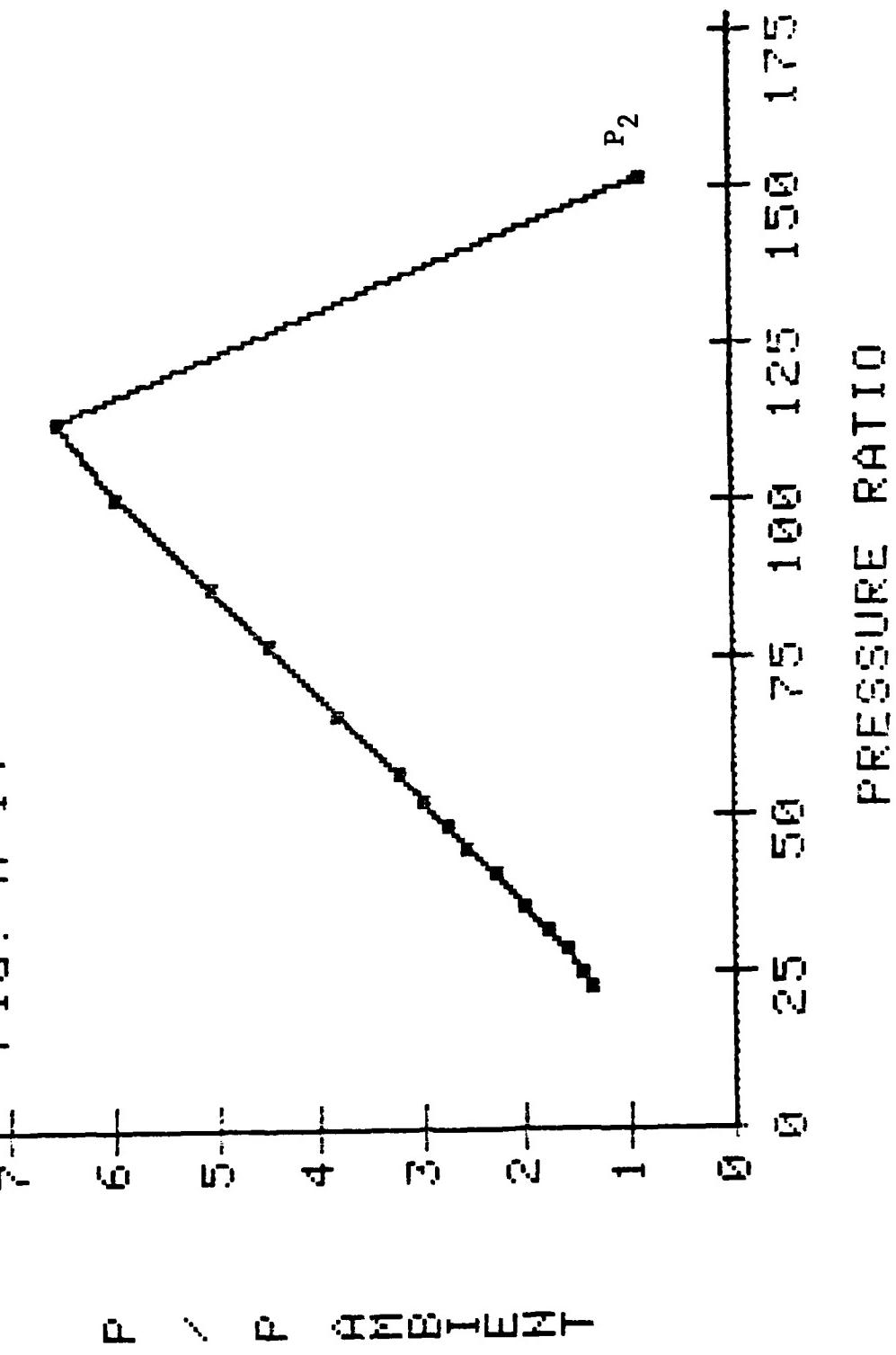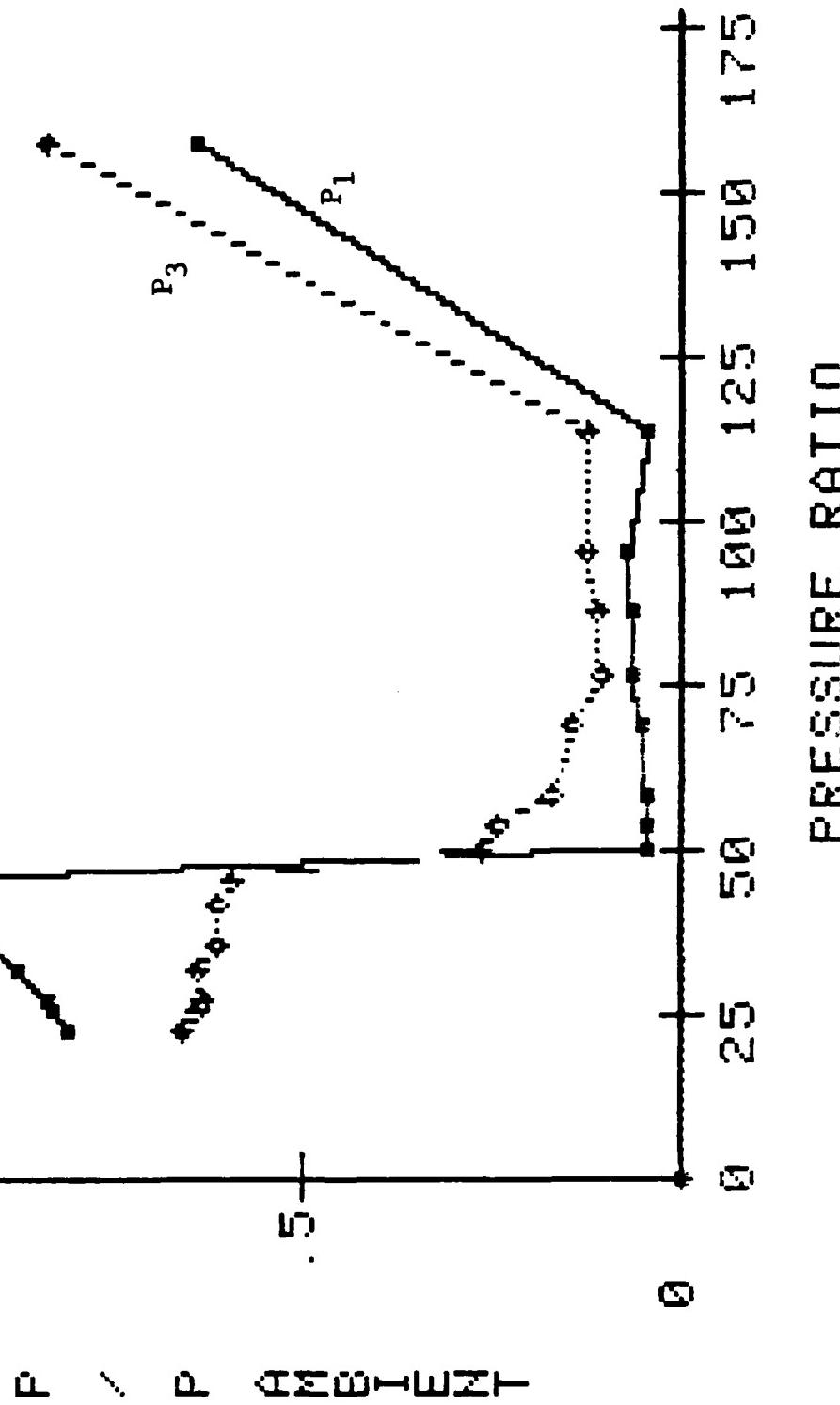
FIG. A-15

Fig A-15. P_1/P_A and P_3/P_A vs PR for Nozzle Set 3

FIG. A-16
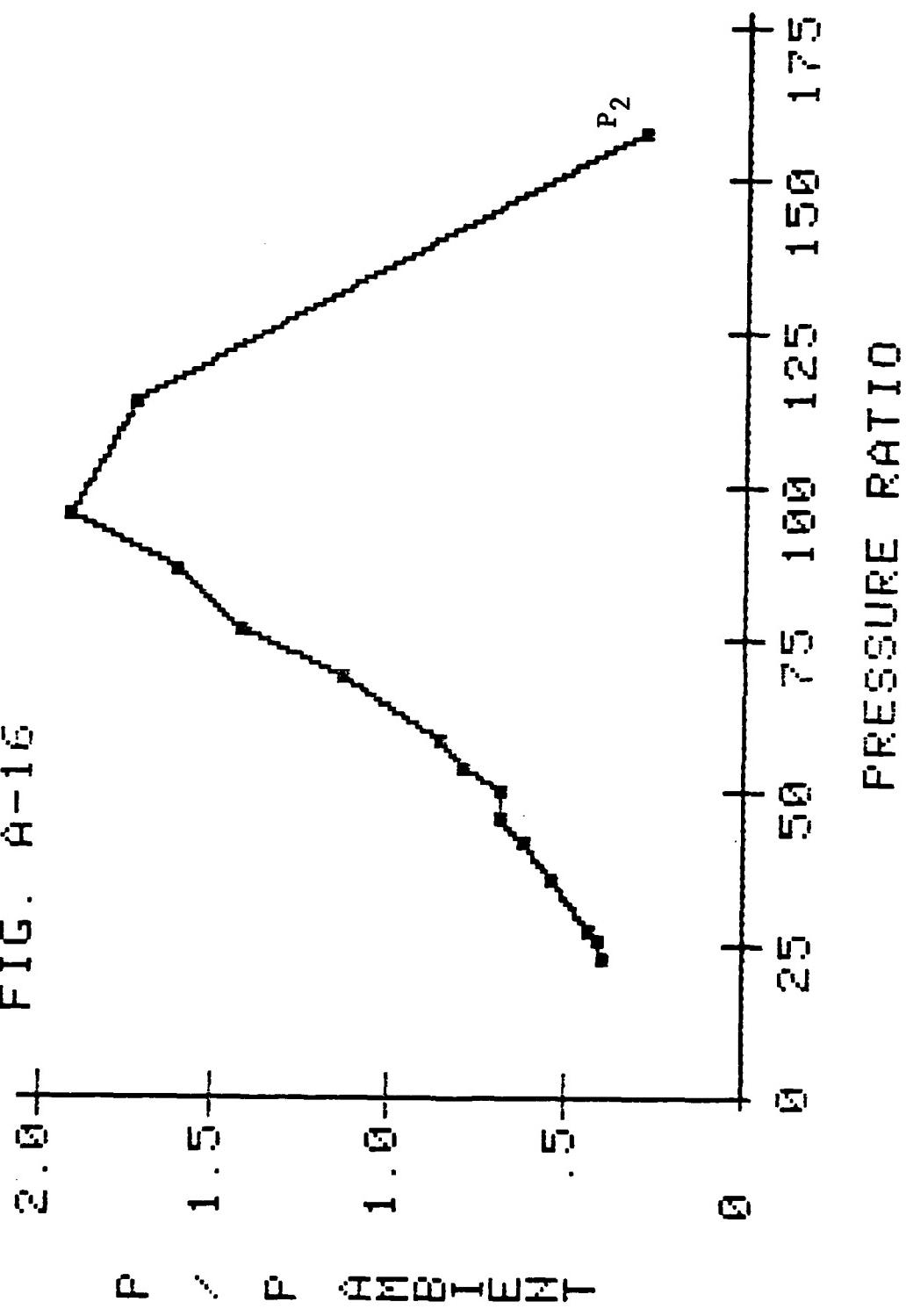
Fig A-16. P_2/P_A vs PR for Nozzle Set 3

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Vita

Captain David R. Bjurstrom was born on 19 May 1951 in Indianapolis, Indiana. In May 1973, he received his BSE degree in Aerospace Engineering from the University of Michigan and was awarded a commission in the USAF through the ROTC program. Following graduation from pilot training in 1974, he flew AC-130 aircraft in Thailand and Florida and was an Instructor Pilot in T-37's in Texas. Captain Bjurstrom then entered the School of Engineering, Air Force Institute of Technology, in May 1983.

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This research involved the construction and employment of hardware for investigating the pressure fields and flow phenomena in the base region of clustered nozzles during cold flow testing. Ambient test conditions simulating altitudes up to 75,000 feet and chamber to ambient pressure ratios up to 200 can be established. The clusters considered were made up of a pair of two-dimensional supersonic convergent divergent nozzles with a design exit Mach number of 3.68. Three nozzle sets were studied; each having different spacing between the nozzles. A Schlieren system that allowed for both still photographs and film was used to supplement the pressure data.

This study indicates that the pressure fields in the base region of a nozzle cluster are heavily dependent on both geometry and on the operating altitude. The outer wall of the test section adjacent to the nozzles was observed to significantly affect the flow patterns and measured pressures. Potential influences on performance exist due both to changes in the gas dynamics of the flow and the appearance of additional pressure-area terms.

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